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TIME DOMAIN ANALYSIS OF ULTRASONIC SIGNALS FOR NON-INVASIVE TEMPERATURE ESTIMATION

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ABSTRACT
A time delay technique that relates the temperature changes with the time shifts (*delays*) presented in echoes coming from a simulated and experimental body immersed in a thermal bath is developed and analyzed. Both simulated and experimental signals were obtained from a numeric and experimental phantom respectively. Results of the time domain analysis for two transducer frequencies in a temperature interval ranging from 25 °C to 42°C are presented. Performance in the technique is evaluated by calculating the correlation coefficient between the lineal regression and the real values obtained for the temperature estimation. A comparison between simulated and experimental data for two transducer frequencies is presented.

INTRODUCTION
During a therapeutic treatment based on the temperature rising through ultrasound or electromagnetic radiation, the knowledge of the heat distribution on the radiated area together with the hot spots location is fundamental. Achieve a quantitative temperature measurement is very important. Nowadays, many different techniques based on Nuclear Magnetic Resonance, Tomography, Impedance measurements and Ultrasound have been developed for non-invasive temperature measurements; nevertheless, Ultrasound presents several advantages over the others above mentioned: 1) ultrasonic radiation is easy to focus, 2) ultrasonic beam does not produce harmful effects, 3) there is compatibility between ultrasound therapy equipments and 4) Ultrasound equipments possesses a relative low cost.

In ultrasound, several techniques for non-invasive temperature estimation have been developed. Some methods employ a time domain analysis to estimate the lag of the echoes coming from a heated body [1][2]; other techniques, developed in the frequency domain, analyze the relationship between temperature changes and frequency components of the RF signal [3]. The work in this paper is focused on the performance of a time domain method, which employs a TDE (*Time Delay Estimation*) technique to relate the echoes' time shifts with temperature.

EXPERIMENTAL DATA ACQUISITION IN A BIOLOGIC PHANTOM
For the analysis of this non-invasive temperature estimation technique, signal acquisition from an experimental tissue mimicking material was necessary. An agar-agar based phantom whose characteristics closely simulate the ultrasound velocity of tissue (1540 m/s) was developed. To emulate a near to regular scattering tissue, 4 layers of evenly spaced glass spheres (1 mm of diameter) with an average spacing between layers of 4 mm were constructed. To achieve a controlled temperature and a good coupling between the transducer and the phantom, the tissue mimicking material was immersed in a bi-distilled water bath. This phantom was ultrasonically interrogated with a 2.25 MHz wideband transducer (Mod. 12C-0204-S Harisonic, USA) and with a 3.5 MHz wideband transducer (Mod. V383-531782, Panametrics, USA). An electronic transceiver (developed in our laboratory), which includes a high-voltage pulse generator, was coupled to a broadband signal amplifier for driving-receiving. The pulse amplitude was 100 V. Resulting signals were acquired, for successive increments of 1 °C within a temperature interval ranging from 25 °C to 42 °C by using a digital oscilloscope (Mod. Wave Runner 6000A, LeCroy, USA) at a sampling rate of 5 GS/s. The waiting time between lectures for each increment (to ensure temperature uniformity inside of the phantom) was not no bigger

than 12 minutes. Five signal acquisitions were performed for each temperature to obtain an averaged signal per each temperature. As a thermometric reference system, an optic fiber thermometry kit (Mod. 3300, Luxtron, UK) was employed.

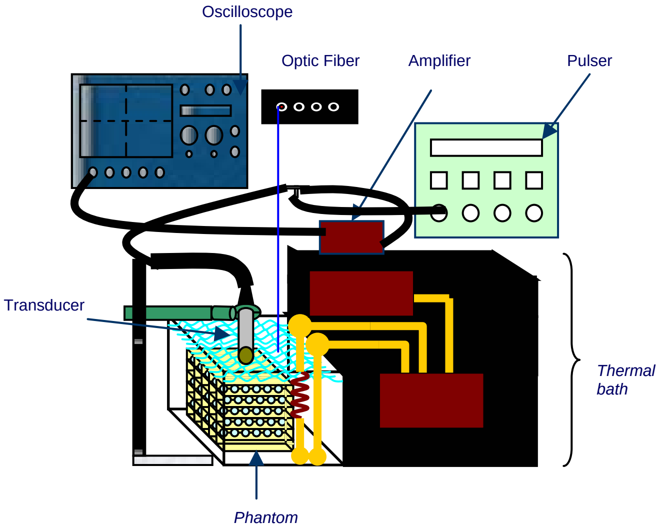


Figure 1.- Experimental setup.

NUMERICAL PHANTOM SIMULATION

Within the framework of our investigation objective, biologic tissue can be considered, from a merely acoustic point of view, as a semi-regular lattice of scatters separated by an average distance "*d*", as other authors suggest [4]. The echo-graphic signal resulted from the reflections of an ultrasonic pulse traveling inside a tissue is a complex sum of echoes, each one with a different time of flight. For simplicity, taking into account that we just want to determine a specific type of phenomena of thermal interest, we used in our analysis a basic model of these echo-graphic effects. For the numeric simulations of the tissue echo-graphic behavior, we considered as a first approximation, that the successive echoes preserved the shape of the incident pulse and just their amplitude is attenuated by the medium effects; so no important dispersion associated to frequency in the attenuation phenomenon are supposed. In addition, punctual reflectors and far-field conditions will be considered in our analysis, and as a consequence, possible diffraction effects due to transducer aperture and/or to reflectors are neglected [5]. A simple pattern of an ultrasonic pulse representing an elementary echo coming from a punctual and ideal reflector in such far-field conditions, can be simulated by a mathematical model, typical in this type of applications [6], which is defined by the following expression:

$$P(t) = -te^{-4B^2t^2} sen(2\pi f_0 t) \qquad 1)$$

where, *B* is the bandwidth, *t* is the time and f_0 is the central frequency.

When an ultrasonic pulse *P(t)*, propagates inside a body that contains evenly spaced reflectors distributed on a line in its central axis, it is reflected and the received signal *r(t)*, in time domain, could be considered as the overlapping echoes produced by each reflector contained inside the body:

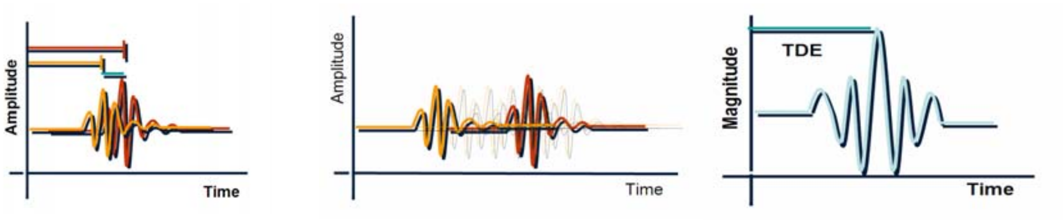
$$r(t) = \sum_{k=1}^{N} a_k P(t - (2x_k / c)) \qquad 2)$$

where a_k is the echo amplitude due to the reflector *k*, *t* is the time, x_k is the position of the reflector *k*, and *c* is the speed of sound [6]. Simulated ultrasonic signals were generated inside of a wide temperature interval (25°C – 42°C), with increments of 1°C, and sampling rate of 1GS/s. Two central frequencies were established: 2.25 MHz and 3.5 MHz.

METHOD DESCRIPTION

A. Cross-Correlation

Cross-correlation in the analysis of rf-backscattering signals is used to estimate the lags of an acquired signal at a final temperature T_f, with respect to a reference signal acquired at an initial temperature T_0. For this purpose, we consider that the signals to be cross-correlated with a reference signal are very similar in shape, frequency and magnitude as depicted in Figure 2. a). This is easy to achieve because the signals that we want to correlate come from the same source. In other words, both signals come from the same scatterers, at different times and at different temperatures.



a) b) c)

Figure 2. Cross-Correlation Technique. a) Two signals coming from the same source, shifted signal (*orange*), reference signal (*red*), b) cross-correlating the signals and c) cross-correlation.

We shifted the delayed signal over the reference signal as depicted in Figure 2. b). In order to calculate the lag we found the maximum correlation coefficient between these two signals and estimated the time delay as shown in Figure 2. c). The cross-correlation function between the received signals that we calculate is given by

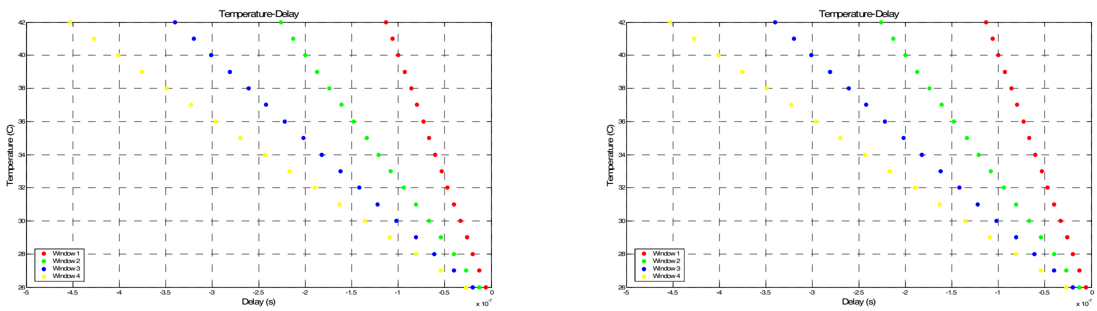
$$R_{12}(t) = E[x_1(t+\tau)x_2^*(t)] = E[x_1(t)x_2^*(t-\tau)] \qquad 3)$$

where R_{12} denotes the cross-correlation between the two signals, x_1 and x_2 are the signals to be cross-correlated, * is the complex conjugate, E[.] is the expected value and τ is the delay [7].

RESULTS

A. Simulation

Once the signals are acquired, we proceeded to separate the echoes in 4 windows. Thus, we correlated 4 echoes at 4 depths (starting from the face of the transducer) with the associated reference signals and finally we obtained the cross-correlation functions for 17 temperatures ranging from 25°C to 42° C. With these data, we calculated the time delays for the 17 temperatures to find the lineal regression that allow us to make non-invasive temperature estimations.



a) b)

Figure 3. a) Time delay estimations for a simulated phantom (2.25 MHz), b) Time delay estimations for a simulated phantom (3.5 MHz).

We observed a lineal behavior of the time delay in function of the temperature for all data windows in a temperature interval ranging from 25°C to 42°C as depicted in Figure 3, and the lineal regression used to estimate temperature was calculated for these curves for both transducer frequencies. The lineal regressions and its correlation coefficients at four different depths for both frequencies that we used to estimate the temperature are shown in Tables I and II. We obtained the same lineal regressions and correlation coefficients for both frequencies.

Table I.- Lineal Regressions for signals of the simulated phantom (2.25 MHz)

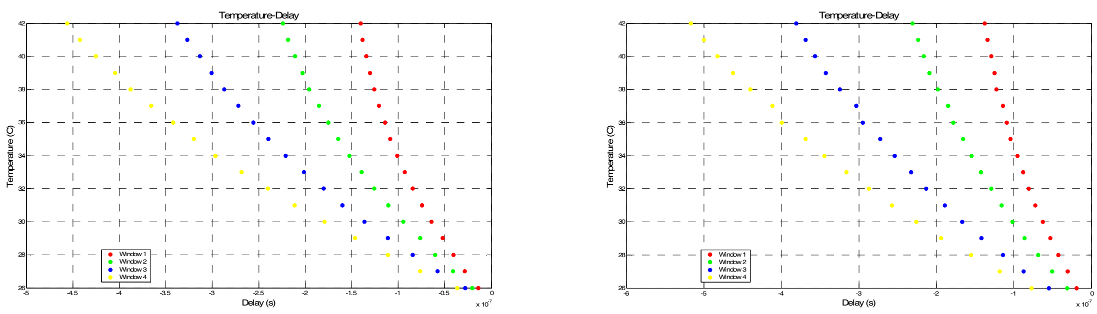
Depth (From de Face of the Transducer)	Linear Regression	Correlation Coefficient. (%)
4 mm	$T(\delta) = -(1.499857 \times 10^{8})\delta + 24.88616$	99.99524
8 mm	$T(\delta) = -(7.509098 \times 10^{7})\delta + 24.87865$	99.99623
12 mm	$T(\delta) = -(5.002114 \times 10^{7})\delta + 24.88438$	99.99662
16 mm	$T(\delta) = -(3.754509 \times 10^{7})\delta + 24.87654$	99.99571

Table II.- Lineal Regressions for signals of the simulated phantom (3.5 MHz)

Depth (From the face of the transducer)	Linear Regression	Correlation Coefficient.
4 mm	$T(\delta) = -(1.499857 \times 10^{8})\delta + 24.88616$	99.99524
8 mm	$T(\delta) = -(7.509098 \times 10^{7})\delta + 24.87865$	99.99623
12 mm	$T(\delta) = -(5.002114 \times 10^{7})\delta + 24.88438$	99.99662
16 mm	$T(\delta) = -(3.754509 \times 10^{7})\delta + 24.87654$	99.99571

B. Experimental

We used two transducer frequencies: 2.25 and 3.5 MHz to acquire the signals as we did for the simulated phantom. Once acquired the signals we separated the echoes in 4 windows. Thus, we correlated 4 echoes at 4 depths (~10 mm, ~14 mm, ~20 mm and ~24 mm) with the associated reference signals in the same way as we did for the simulated phantom; finally we obtained the cross-correlation functions for 17 temperatures ranging from 25°C to 42° C. With these data we calculated the time delays for the 17 temperatures in order to make a lineal regression that allow us to make non-invasive temperature estimations.



a) **b)**

Figure 4. a) Time delay estimations for a experimental phantom (2.25 MHz), b) Time delay estimations for a experimental phantom (3.5 MHz).

We observed for the experimental data a quasi-lineal behavior of the delay in function of temperature for all data windows in a temperature interval ranging from 25°C to 42°C as depicted in Figure 4, and the lineal regression used to estimate temperature from the data was calculated for these curves for both transducer frequencies as we did for the simulated signals. The lineal regressions and its correlation coefficients at four different depths for the frequencies 2.25 MHz and 3.5 MHz that we used to estimate the temperature for the experimental data are shown in Tables III and IV. We obtained almost the same lineal regressions for both frequencies.

Table III.- Lineal Regressions for the signals of the experimental phantom (2.25 MHz)

Depth (From the face of the transducer)	**Linear Regression**	**Correlation Coefficient. (%)**
10 mm	$T(\delta) = -(1.228235\times10^{8})\delta + 22.66050$	97.98624
14 mm	$T(\delta) = -(7.708109\times10^{7})\delta + 23.10028$	98.69043
20 mm	$T(\delta) = -(5.127679\times10^{7})\delta + 23.38782$	99.08327
24 mm	$T(\delta) = -(3.775967\times10^{7})\delta + 23.51103$	99.23644

Table IV.- Lineal Regressions for the for signals of the experimental phantom (3.5 MHz)

Depth (From the face of the transducer)	**Linear Regression**	**Correlation Coefficient. (%)**
10 mm	$T(\delta) = -(1.329539\times10^{8})\delta + 22.15694$	98.61965
14 mm	$T(\delta) = -(8.053149\times10^{7})\delta + 22.24477$	99.16215
20 mm	$T(\delta) = -(4.942278\times10^{7})\delta + 22.16208$	99.32968
24 mm	$T(\delta) = -(3.63185\times10^{7})\delta + 22.15440$	99.32950

CONCLUSIONS

We presented here a comparison between the results obtained for a non-invasive temperature estimation using a time domain technique based on the cross-correlation of signals coming from numeric and experimental phantoms. As we can see, this work shows very good results for the non-invasive temperature estimation using a time domain technique that calculates the time delays presented in the echo signals when its temperature is incremented. In the numeric phantom we saw a linear behavior due to the basic parameters that we were simulating. The echoes coming from the numeric phantom were separated always by the same distance "*d*" and so, we obtained a uniformly echo distribution; also the time delays for temperature increment were very linear and thus we obtained a very linear behavior. This is shown in table I (225 MHz) and in table II (3.5 MHz) where we presented the linear regressions and the correlation coefficient obtained for the numeric phantom.

We also obtained an average correlation coefficient of 99 % for the experimental phantom, though it was not perfect in some parameters that we expected. For example we could not achieve a uniform distance *d* (4 mm) in all the scatterers' lattice, instead, we had an approximated distance *d*, which varied in some areas of the phantom. The most important variation from the experimental respect to our numeric phantom is found between the second and third layers where the maximum variation of *d* is ~ 50 %. In other words if *d* = 4 mm, in this case *d* ~ 6 mm. Other important difference presented was that numeric phantom signals simulate that the transducer is also at the same distance *d* (4 mm) from the first scatterer, no in the same way for our experimental phantom where this distance was ~10 mm. We took this into account in our results and as we could see in table III (2.25 MHz) and table IV (3.5 MHz) the linear regressions and the correlation coefficients that we obtained for the experimental signals showed to be good enough to be used in non-invasive temperature estimation. Based on the results obtained for the experimental data, the time delays were not the same for both frequencies (2.25 MHz and 3.5 MHz) as it was for the numeric phantom, but they were very close between them as we expected, it was obvious since, the transducers were not placed over the same phantom's area. Though we tried to achieve this condition it was impossible due to the transducers' different dimensions that caused that our transducers were not covering exactly the same area, but we were very close to achieve it.

We observed also, that we had smaller delays for smaller depths and bigger delays for greater depths; this is showed in Figure 3 (numeric phantom) and Figure 4 (experimental phantom). According to this, we can say that we have a better resolution for the estimated time delays when we work in the near field of the transducer than when we work in the far field. A better resolution in the calculus of the time delays implies a better resolution of our noninvasive temperature estimation. To have a better approximation in the temperature estimation we employed a quadratic regression which fits better into our measured data and thus better results are obtained, these results are not presented in this paper but will be presented in a further work.

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